DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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MONTHLY WEATHER REVIEW

Editor, JAMES E. CASKEY, JR.

Volume 79
Number 8

AUGUST 1951

Closed October 15, 1951
Issued November 15, 1951

SOME CHARACTERISTICS OF THE EPPLEY PYRHELIOMETER

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[Manuscript received May 23, 1951]

ABSTRACT

Tests were made of the effect of several variables on the performance of the Eppley pyrheliometer. The tests showed: (1) How the output increased with decreasing ambient temperature; (2) how output varied with angle of incidence of collimated radiation; (3) that output decreased about 5 percent when receiver was exposed in the vertical plane, but that complete inversion from the horizontal had no significant effect; and (4) that a few water droplets on the glass envelope did not influence output. In addition, spectral transmission data, from National Bureau of Standards tests, are shown.

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INTRODUCTION

Recent measurements of solar radiation by means of Eppley pyrheliometers mounted on aircraft [1] have made it desirable to determine the response of that instrument under some of the conditions of exposure in flight and the variation in response characteristic of pyrheliometers exposed under similar conditions. Tests giving some of these data (on effects of temperature, and "cosine response" primarily) have been completed at the Instrument Division of the Weather Bureau, and it is the purpose of this paper to report the results and compare them with other available similar data. Also included are data on spectral characteristics, obtained by the National Bureau of Standards for the Weather Bureau.

THE EPPLEY PYRHELIOMETER

The Eppley pyrheliometer (fig. 1) consists of a thermopile mounted under receivers inside a clear glass spherical bulb about 3 inches in diameter. The thermocouples are platinum-rhodium (90-10 percent) and gold-palladium (60-40 percent) [2] and the thermopile comprises either ten or fifty thermocouples [2] depending on the output the particular instrument was designed to produce. The receivers are concentric flat metal rings exposed in a common plane; the rings are thermally insulated from each other and from the mounting. One ring is coated with magnesium oxide; to the underside of this the electrically insulated cold junctions are attached in close thermal contact. The other ring is coated with lampblack; the hot junctions are similarly attached to its undersurface. The magnesium oxide has a high reflectivity for radiation in the solar wave lengths and is a good absorber and emitter in the longer wave lengths (e. g. [3], p. 2241), making for a low equilibrium temperature on exposure to solar radiation. Lampblack has good absorption

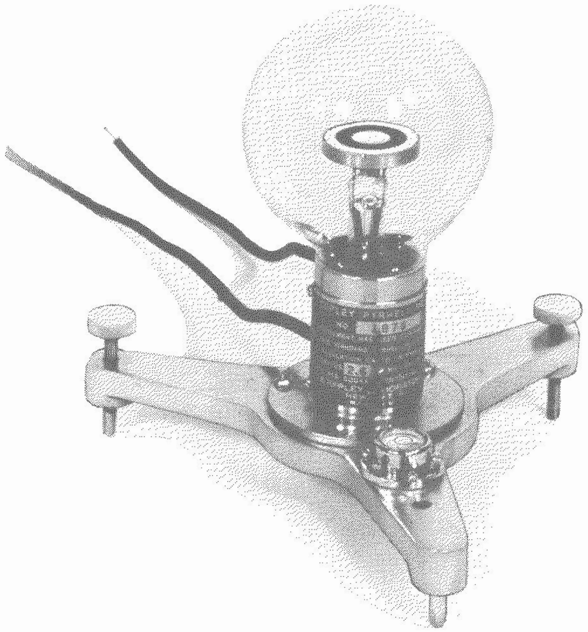

FIGURE 1.—The Eppley pyrheliometer.

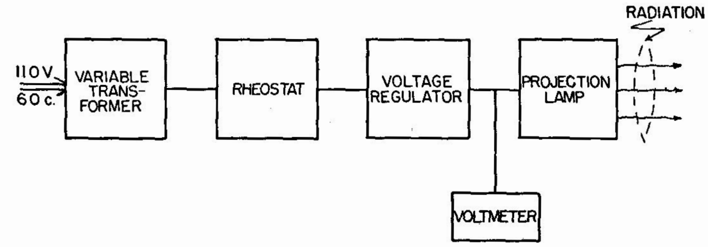

FIGURE 2.—Block diagram of radiation-generating equipment used in tests.

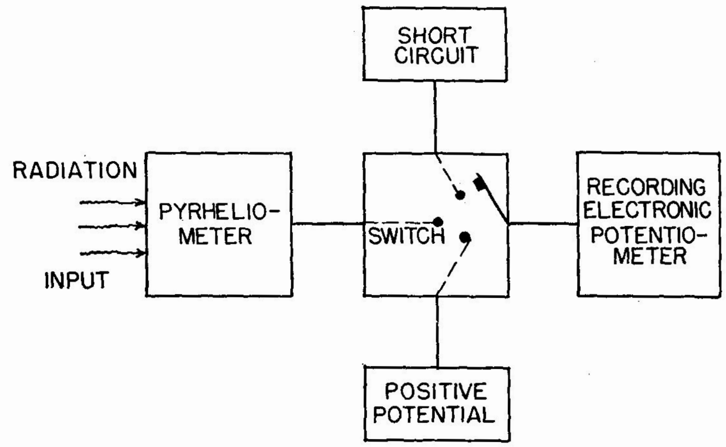

FIGURE 3.—Block diagram of pyrheliometer and output-measuring circuit used in tests.

characteristics in both wave length intervals, and due to its greater absorption of the solar wave lengths its equilibrium temperature on exposure to solar radiation is higher than that of the magnesium oxide. The similarity of the receivers with regard to absorption of long wave radiation tends to minimize the effect of any long wave radiation (as from the glass cover) which may fall on the receivers. The bulb contains dry air [2]. The over-all response of the instrument to solar radiation is an e. m. f. rather closely proportional to solar radiation flux density through the plane of the receivers.

EQUIPMENT USED IN TESTS

The equipment for examining the effects of temperature and angle of incidence ("cosine response") on the response of the Eppley pyrheliometer consisted of (*a*) a radiation-generating unit, (*b*) mounting for the pyrheliometer on either a moveable disc or inside a "temperature box," and (*c*) a recording potentiometer. Figure 2 is a block diagram of the radiation generating part of the equipment. Voltage from the 110-volt, 60-cycle, 1-phase line was brought to approximately 100 volts in the variable transformer and more exactly to that value in the rheostat, and was stabilized by a voltage regulator. It was necessary to monitor the voltage across the lamp with a voltmeter to guard against any persistent small variations in the line voltage. A mazda projection lamp whose radiation output was quite stable, as indicated by periodic checks by the National Bureau of Standards, was the source of radiation. Figure 3 is a block diagram showing the pyrheliometer (which was mounted on a movable disc or in the temperature box or on a rotating channel iron) and output-measuring circuit. The output leads from the pyrheliometer were brought to the recording potentiometer through a switching arrangement for convenience in making zero reference marks and time checks on the record. The recorder input leads could be short-circuited to move the pen downscale, or switched to a source of positive potential for an up-scale reference mark.

TEMPERATURE TESTS

TEMPERATURE BOX

The temperature box (fig. 4) used in making temperature tests was made up of two sections. One section for dry ice was situated above the other section, the radiation chamber, in which the pyrheliometer was mounted. The two sections were connected by adjustable louvres. For the low temperature values, air was forced by a fan over the dry ice down through one louvre into the radiation chamber, and returned to the dry-ice compartment upward through the second louvre. There was enough turbulence to keep the air well mixed. For high temperatures the louvres were closed and electric current was metered by means of a variable transformer into heating coils located in the radiation chamber. By these means, temperature could be kept at any level between $-40°$ F. and $+120°$ F., to within 2° or 3°. Radiation from the lamp was admitted through a glass window in the side of the radiation chamber to fall on the vertically-mounted pyrheliometer. The flux density was about a half langley per minute, as shown by the pyrheliometers.

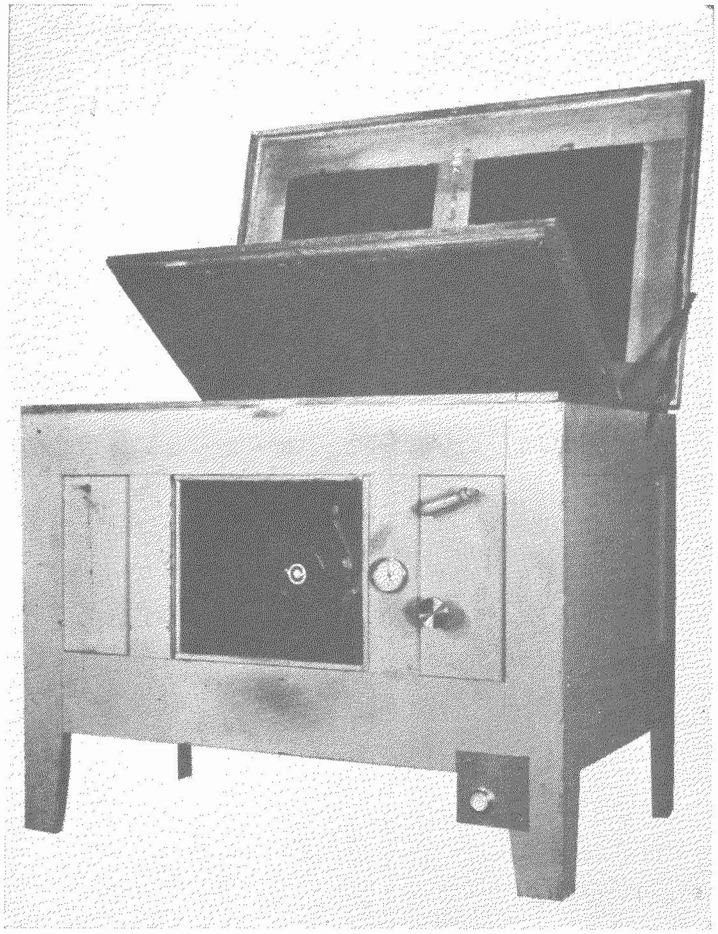

FIGURE 4.—Temperature box used in tests.

Beginning at 80° F., temperatures were varied by 40° increments and kept at each test point for about 25 minutes. It was necessary to hold the temperatures constant over this rather large time interval to avoid the effects of a substantial "overshoot" of pyrheliometer response. For colder temperatures the equilibrium response is higher than for warmer temperatures Nevertheless, with rapid lowering of temperature from one test point to another, the response would increase by a few percent *above* its equilibrium value for the colder test point. The response then gradually diminished to equilibrium during a period of 20 minutes or so depending on the preceding time-rate-of-change of temperature. An increase in temperature resulted in a corresponding *undershooting* of equilibrium response. It will be recognized that this effect differs from an ordinary "lag" effect. (The instrument would not be affected in this way by rates of change of temperature associated with weather.)

RESULTS OF TEMPERATURE TESTS

Figure 5 shows data obtained for five pyrheliometers, plus data obtained previously for two others by the National Bureau of Standards [6]. (The original Bureau of Standards data were given in more detail, being given at increments of 10° C.) The data are also given in table 1. The responses are in terms of response at 80° F. which is arbitrarily assigned the value of 100 percent.

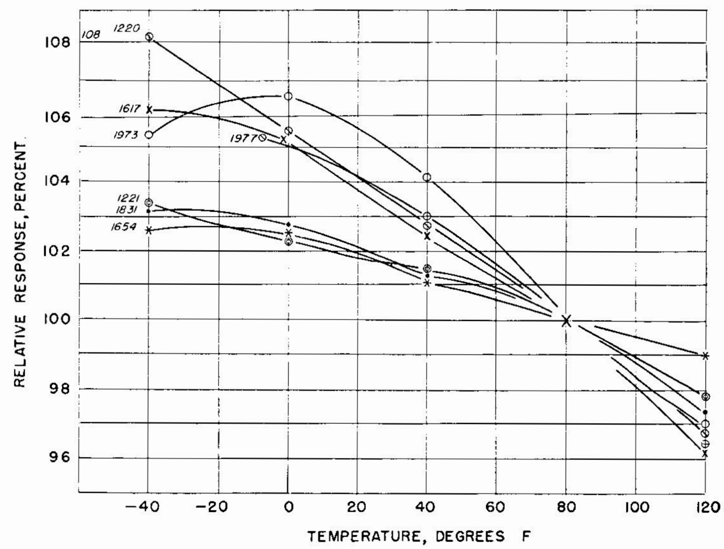

FIGURE 5.—Relative response as a function of temperature, for five pyrheliometers (Nos. 1617, 1654, 1831, 1973, and 1977) tested by Weather Bureau and two others (Nos. 1220 and 1221) tested by National Bureau of Standards [6].

TABLE 1.—*Effect of ambient temperature on response of Eppley Pyrheliometers. Tabulations of response are given in percent of response at 80° F.*

Temperature		Pyrheliometers No.—							Average (of the 7)
		1617	1654	1831	1973	1977	1220	1221	
° C.	° F.	Weather Bureau tests					Bureau of Standards tests		
−40	−40	106.2	102.7	103.1	105.4	----	108.1	103.3	104.8
−17.8	0	105.2	102.5	102.7	106.5	105.1	105.5	102.4	104.3
+4.4	+40	102.4	101.1	101.1	104.1	103.0	102.8	101.4	102.3
+26.7	+80	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
+48.9	+120	96.2	99.0	97.3	97.0	96.4	96.7	97.8	97.2

CAUSES OF TEMPERATURE EFFECTS

It will be noted that the response decreases with higher temperatures. This appears to be due to a decrease in the difference in temperature between the black and white receivers rather than a diminution of the "efficiency" of the thermocouples comprising the thermopile. By efficiency is meant the output per degree of temperature difference between hot and cold junctions. This can be seen from the performance equation of one thermocouple of the kind comprising the pile [4]:

$$E=32.975\ T+.03881\ T^2 \tag{1}$$

where T is the temperature of the hot junction in degrees Centigrade, the cold junction being at zero; E is e. m. f. in microvolts (μV). This implies (e. g., Loeb [5]) the relationship

$$E=32.975\ (T_h-T_c)+.03881\ (T_h^2-T_c^2) \tag{2}$$

where the subscripts h and c indicate hot and cold junctions, respectively. If the difference of temperature between the two junctions is assumed to remain a constant, k,

$$E=32.975k+.03881k(2T_h-k) \tag{3}$$

$$dE=\frac{\partial E}{\partial T_h}\,dT_h=.07762k\,dT_h. \tag{4}$$

This shows that an increase of .0776 μV in e. m. f. output should occur for each 1° C. increase in the temperature of the hot junction (provided a one degree temperature difference between the hot and cold junctions is maintained), for each thermocouple in the thermopile. Since (with constant radiation) the output of the pyreheliometer *diminishes* with increasing ambient temperature instead of increasing as equation (4) suggests should be the case, it appears that the temperature difference between the hot and cold junctions diminishes with increasing ambient temperature. This may be due to convection inside the glass bulb. Convection effects may also explain the diminishing output of the pyrheliometer when exposed in the vertical plane as will be described later.

COSINE RESPONSE TESTS

PYRHELIOMETER MOUNTING

For the cosine response tests, i. e., tests of the effect of the angle of incidence on response, the pyrheliometer was mounted on a pair of plates taken from an old surveying level. The fixed plate was marked in degrees and fractions and the rotating plate, to which the pyrheliometer was rigidly fixed, contained a vernier for accurate reading of the angular displacement from the zero reference mark of the fixed plate. Unwanted reflections from extraneous sources were suppressed by draping the reflecting surfaces with black cloth. Figure 6 shows the equipment with some of the radiation-shielding cloth removed (recording equipment is not shown). The pyrheliometer was mounted vertically so the axis of rotation of the plate was in the plane of the black and white annular receivers—that is, the axis of rotation coincided with the vertical diameter of the receiver. The center of the receiver was also in the center of the horizontally-directed radiation beam. Levels and a cathetometer, shown in figure 6, were used in this alignment. Rotation of the plate changed the angle of incidence of the radiation on the receiver by an amount indicated by the vernier. Since the area of the beam (as measured in a plane normal to its direction of propagation) intercepted by the receiver was proportional to the cosine of the angle of incidence, the e. m. f. should have been proportional to the cosine of the angle of incidence if the instrument had been perfect (perfect, that is, in that for a given flux density across the plane of the receiver the response should be independent of the angle of incidence; and for any fixed angle of incidence the response should be linear with radiation flux density).

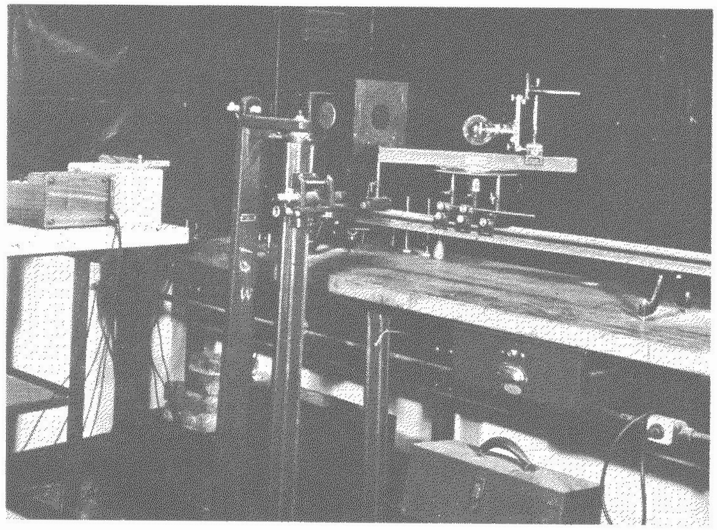

FIGURE 6.—Mounting of pyrheliometer and other equipment used in cosine response tests. Recording equipment is not shown.

RESULTS OF COSINE RESPONSE TESTS

Two pyrheliometers were tested. Figure 7 shows the results obtained from the present tests (for pyrheliometers 1754 and 1973) and data obtained in similar tests by the Bureau of Standards [6] (for pyrheliometers 1220 and 1221). The data are also given in table 2 (Bureau of Standards data were for 10° increments of angle of incidence; part of data is omitted in this table). Woertz and Hand [7] made tests using different techniques, but analysis of their data indicates similarity to the other response curves (except No. 1754).

For perfect calibration, all of the points in figure 7 should have coincided with the solid line. It is difficult to judge from this the percent of error associated with the points. To illustrate the percent of the true response actually given by the pyrheliometers, the ratio of the ordinates of the points in figure 7 to the corresponding ordinates of the true cosine curve were computed and the results are shown in figure 8. The various pyrheliometers show fair agreement except for No. 1754. That instru-

TABLE 2.—*Effect of angle of incidence on response of Eppley pyrheliometers. Tabulations are the percent of the correct response shown by the instruments at different angles of incidence α. Response is arbitrarily assumed 100 percent at $\alpha=0$.*

Angle of incidence α	Pyrheliometers No. —			
	1754	1973	1220	1221
	(Weather Bureau tests [1])		(Bureau of Standards tests [2])	
0	100	100	100	100
30	103	100	102	102
60	105	101	100	99
70	------	-----	94	96
75	101	-----	-----	-----
80	------	79	81	82
85	103	-----	-----	-----
90	$+\infty$ in 3 of 4 paths	$+\infty$	$-\infty$	$-\infty$

[1] Results given are averages of 4 paths.
[2] Results given are averages of 2 paths.

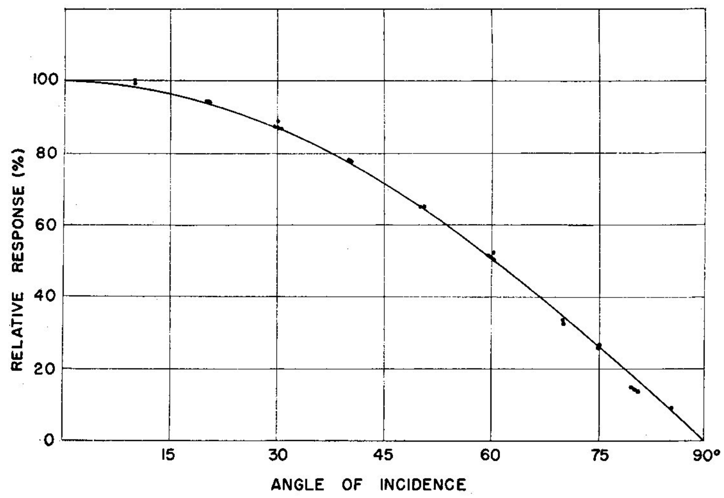

FIGURE 7.—Relative response as a function of angle of incidence of collumated radiation, for two pyrheliometers (Nos. 1754 and 1973) tested by Weather Bureau and two others (Nos. 1220 and 1221) tested by National Bureau of Standards [6]. Response assumed correct at zero angle of incidence. Curve is theoretically perfect response, i. e., cosine of angle of incidence.

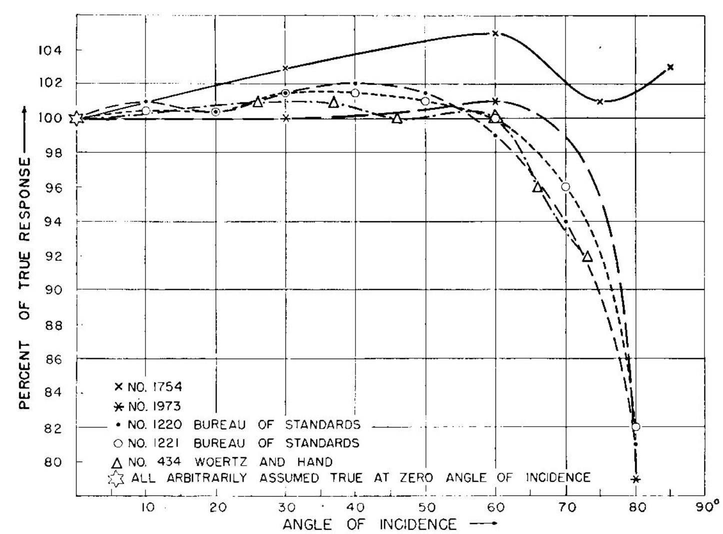

FIGURE 8.—Percent of true response as a function of angle of incidence computed for data given in figure 7 and for data from a test by Woertz and Hand [7].

ment showed a higher response near 80° angle of incidence than the others. (Woertz and Hand data went only to 78°. The response at $\alpha=\cos^{-1}$ 0.9, about 25°, was arbitrarily assumed to be 101 percent since normal incidence response was not indicated.)

CAUSES OF COSINE EFFECTS

The deviations from "true calibration" with angle of incidence could be due to either or both of two classes of effects: (*a*) Nonlinearity of e. m. f. with radiation flux density, or (*b*) dependence of response on angle of incidence, assuming constant flux density through the plane of the receivers. It seems to have been generally assumed that (*a*) is unimportant as compared to (*b*), and in previous cosine tests (*a*) was not mentioned as a possible factor in the observed cosine response. Several causes

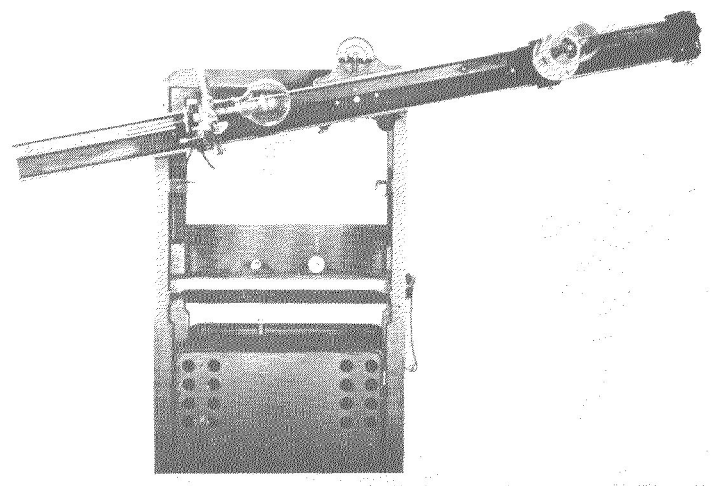

FIGURE 9.—Mounting of pyrheliometer for testing effect of variations in inclination of plane of the receiver. The pyrheliometer is at the left, the radiation lamp at the right.

have been suggested for (*b*), among them the possible dependency on angle of incidence of the absorption of the lampblack (Miller, [8], [9]). Woertz and Hand [7] suggested among other possibilities that the black and white receivers might not be in exactly the same plane, and that irregularity in the glass envelope might be a factor. It might be noted that if (*a*) is of the same general order of magnitude as (or greater than) (*b*), the cosine response curve will be affected significantly by flux density (as measured on a surface normal to the direction of propagation of the radiation beam). This remains to be determined.

MISCELLANEOUS TESTS

EFFECT OF MOUNTING PYRHELIOMETER VERTICALLY

In order to test for variations in pyrheliometer output with inclination of the plane of the receiver, the pyrheliometer and lamp were rigidly mounted about 2 feet apart on a section of channel iron. The arrangement was such that radiation from the lamp was incident on the pyrheliometer at an angle of incidence (approximately "normal incidence") which was unchanged as the iron was rotated through a vertical plane about a pivot in the center of the long axis of the channel iron. (See fig. 9.) The pyrheliometer was protected from random reflections by a shield constructed from an old camera bellows. It was necessary to force-ventilate the pyrheliometer by means of an independently mounted blower to avoid temperature rises. As a control, a photo-voltaic cell was mounted in a similar way, and showed no variation in output when the rail was rotated in steps.

Tests were made with two pyrheliometers. The results showed no significant change in output for the inverted position as compared with the horizontal position, but indicated a decrease of 4 or 5 percent in output when the pyrheliometer receiver was in the vertical plane. This may have been due to convection current effects within the pyrheliometer glass envelope.

These results suggested that the temperature response data might have been influenced by the mounting of the pyrheliometer with the receiver in the vertical plane. To check this, an arrangement was made whereby the pyrheliometer was mounted with the receiver horizontal and facing up. Radiation coming through the window of the temperature box was then reflected to the pyrheliometer by a mirror. The temperature curve obtained with the original vertical mounting was repeated without significant variation; apparently the temperature effect is the same for horizontal and vertical positions of the pyrheliometer.

EFFECT OF WATER DROPS ON THE PYRHELIOMETER

In order to determine whether raindrops would affect the radiation measurements by the pyrheliometer significantly, a pyrheliometer was exposed on the roof, and sprinkled with water from a sponge. While it would have been easy to detect a change in output of well under 1 percent, no change was detected. Evidently the effect of a few raindrops on solar radiation measurements with the pyrheliometer is negligible.

SPECTRAL TRANSMISSION OF GLASS ENVELOPE

The National Bureau of Standards has made for the Weather Bureau tests of the transmission of two samples of the glass from which the pyrheliometer covers are made. The following is from the Bureau of Standards letter of transmittal:

"* * * With reference to the conference on Tuesday, March 27, 1951, between Messrs. Norman B. Foster and Torrence MacDonald of the U. S. Weather Bureau and members of the Radiometry Laboratory of this Bureau, transmission measurements have been made on samples of glass taken from two Eppley pyrheliometer glass envelopes previously submitted to this laboratory by the Eppley Laboratory. For these tests sections of about 1 by 1 inch were taken from the upper one-half of the bulb hemisphere (centered about midway between the zenith and horizontal positions). In the case of each bulb the thickness ranged from about 1.0 mm. at the zenith to about 0.5 mm. at the horizontal position. Hence, the samples examined were wedge shaped. This fact coupled with the curvature of the specimens rendered precise transmission measurements difficult. Transmission measurements through the ultraviolet, visible, and to 1100 millimicrons in the infrared as obtained with a Bechman quartz spectrophotometer are given in the accompanying table. Spectrograms as obtained with a Perkin-Elmer double-beam infrared recording spectrophotometer are enclosed for the infrared spectral region. Because of the peculiar focusing effects resulting from the curvature and wedge shape of the samples the transmission data are subject to small indefinite errors. In particular in the case of the infrared curve for sample No. 1, the ordinates should probably be multiplied by about 1.02. An additional correction is required in the case of the infrared curves because of the slight drift of the 100-percent instrument response as a function of wave length. The ordinates for the sample curve are simply to be divided by value recorded on the 100-percent curve."

The tests were made by Ralph Stair, Physicist, of the Radiometry Laboratory of the Bureau of Standards, who signed the letter of transmittal.

The table enclosed with the letter is shown here as table 3. Data were extracted from infrared spectrograms

TABLE 3.—*Transmission measurements for wave lengths from 0.280 to 1.100 microns made on samples of glass from two Eppley pyrheliometer bulbs. Measurements obtained with a Bechman quartz spectrophotometer by National Bureau of Standards*

Wave length (microns)	Transmittance (percent)		Wave length (microns)	Transmittance (percent)	
	Bulb No. 1 (thickness =0.78 mm.)	Bulb No. 2 (thickness =0.79 mm.)		Bulb No. 1 (thickness =.078 mm.)	Bulb No. 2 (thickness =0.79 mm.)
0.280	1.8	1.0	0.370	91.2	91.5
0.290	10.4	7.1	0.380	91.4	91.5
0.300	30.9	25.4	0.390	91.5	91.5
0.310	55.0	50.2	0.400 to 0.900	91.5	91.5
0.320	73.3	70.3	0.950	91.5	91.0
0.330	83.5	82.0	1.000	91.5	90.3
0.340	88.8	87.5	1.050	90.8	89.0
0.350	90.3	90.0	1.100	90.6	88.4
0.360	91.0	91.2			

TABLE 4.—*Transmission measurements for the infrared spectral region made on sample of glass from two Eppley pyrheliometer bulbs. Measurements taken from spectrograms obtained with a Perkin-Elmer double-beam infrared recording spectrophotometer by National Bureau of Standards*

Wave length (microns)	Transmittance (percent)		Wave length (mircons)	Transmittance (percent)	
	Bulb No. 1	Bulb No. 2		Bulb No. 1	Bulb No. 2
1.1	89.4	90.5	3.85	65.7	59.9
1.2	89.6	90.6	3.9	66.2	60.4
1.3	89.7	90.5	3.95	66.6	60.8
1.4	89.9	90.4			
1.5	89.9	90.4	4.0	66.7	61.0
1.6	89.9	90.4	4.05	66.8	61.0
1.7	89.9	90.6	4.1	66.5	60.3
1.8	89.9	90.6	4.15	64.9	58.9
1.9	89.9	90.6	4.2	62.7	56.3
			4.25	62.2	55.9
2.0	89.8	90.5	4.3	61.6	55.7
2.1	89.7	90.3	4.35	56.1	48.0
2.2	89.7	90.2	4.4	49.2	39.7
2.3	89.7	90.2	4.45	43.9	34.4
2.4	89.7	89.9	4.5	37.5	27.7
2.5	89.6	89.7	4.55	31.7	22.2
2.6	89.4	89.4	4.6	26.1	17.3
2.7	89.1	89.4	4.65	21.3	13.3
2.75	86.7	86.2	4.7	17.8	10.9
2.8	76.7	73.7	4.75	14.8	7.3
2.85	72.8	68.6	4.8	13.8	6.5
2.9	72.1	68.0	4.85	13.2	5.6
			4.9	12.7	5.0
3.0	71.8	68.0	4.95	12.0	4.4
3.1	72.0	68.2			
3.15	71.9	67.9	5.0	8.9	3.5
3.2	71.1	66.6	5.05	6.8	2.4
3.25	70.0	65.1	5.1	4.3	1.8
3.3	69.0	63.3	5.15	2.4	1.0
3.35	67.7	61.9	5.2	1.8	.6
3.4	66.6	61.2	5.25	1.4	.5
3.45	65.6	60.3	5.3	1.0	.4
3.5	65.0	59.7	5.35	.6	.2
3.55	64.7	59.4	5.4	.4	.1
3.6	64.6	59.1	5.45	.3	.1
3.7	64.6	59.0	5.5	.2	.0
3.75	64.6	59.0	5.6	.1	.0
3.8	65.0	59.3	5.7	.0	.0

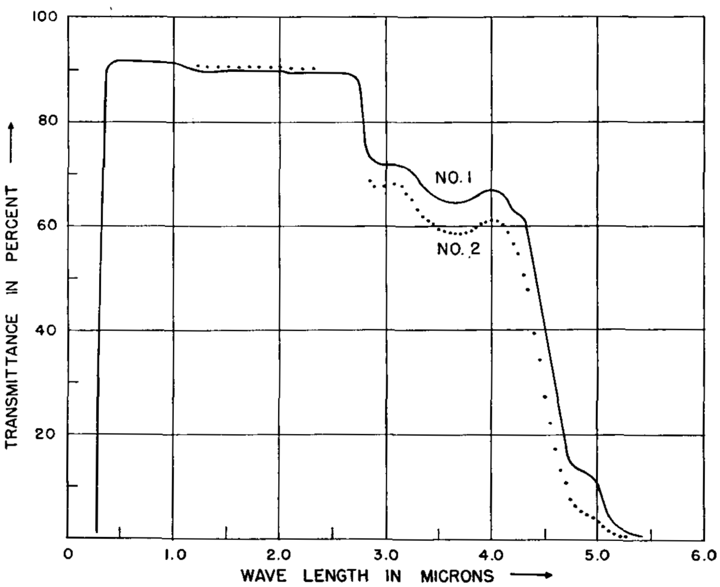

FIGURE 10.—Transmittance of glass samples from pyrheliometer bulbs No. 1 and No. 2, as a function of wavelength. From tests by National Bureau of Standards.

of the Perkin-Elmer spectrophotometer, corrected for zero and for 100 percent drift. These data appear in table 4. Ordinate values of sample 1 were multiplied by 1.02 as suggested in the letter of transmittal. Figure 10 is a graph based on data from tables 3 and 4.

CONCLUSIONS

The tests described suggest that the ultimate accuracy of the pyrheliometer may be more closely approached by considering the cosine and temperature effects. They also provide a partial basis for estimating accuracy of measurements "in the field," where such calibrations are ordinarily unavailable, and where the cost in time and money of obtaining such calibrations and applying them routinely might not justify their use. They indicate that rain droplets do not influence the readings appreciably; they also indicate that measurements taken with the pyrheliometer in the vertical plane are about five percent too low. The Bureau of Standards spectral transmission data indicate that transmission of the glass cover is practically constant over substantially all of the solar radiation spectrum.

ACKNOWLEDGMENTS

As explained in the text, the data on which this report is based were from two sources: (1) National Bureau of Standards Radiometry Section of the Division of Optics, Dr. Curtis J. Humphreys and Ralph Stair, Physicist, and (2) Weather Bureau Instrument Division, by Mr. Norman Foster and the writer. The assistance of Mr. Ruben Guenthner of the Instrument Division is gratefully acknowledged, as are the numerous useful suggestions by S. Fritz of the Weather Bureau Scientific Services Division. We are also indebted to Mr. Raymond Teele of the Bureau of Standards, whose staff checked the standard lamps.

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